EXPERIMENTS ON THE ABSORPTION OF X-RADIATION OF SHORT WAVE-LENGTH, AND ON THE ASSOCIATED SCATTERED AND CORPUSCULAR RADIATION.

By R.T.Dunbar, M.A., B.Sc.

(Thesis for the Degree of Doctor of Philosophy.)

June 1924.

Experiments on the Absorption of X-radiation of short wave-length, and on the associated Scattered and Corpuscular Radiation.

The experiments about to be described were commenced in October 1919. Their purpose was to investigate the origin and exact nature of certain irregularities in the absorption of hard X-rays by light elements which appeared in the experiments of Barkla and White.* In comparing the absorption-coefficients for aluminium, paper, water and paraffin-wax with that for copper over a range of wave-lengths from 0·5 to 0·15 A°, approximately, they found discontinuities which closely resembled those associated with the K, L, ... series of spectral lines, and strongly suggested the existence of a new series of spectral lines. With X-radiation of gradually decreasing wave-length, the absorption-coefficient normally decreases steadily, but when the wave-length of a spectral line characteristic of the substance is passed, the absorption-coefficient for the substance is found to increase rather abruptly to a maximum, when it again begins to decrease normally with decreasing wave-length. The irregularities discovered by Barkla and White were of this character, and, in addition, with decreasing wave-length, the discontinuities for the different substances appeared in the order of their atomic-weights, which is also character-

* Barkla and White, P.M. Oct. 1917.

istic of the discontinuities associated with the K, L, ... series of radiations. The X-ray energy absorbed by matter, so far as we know, reappears in three forms only, (1) scattered X-radiation, which has nearly, if not the same, wave-length as the absorbed radiation, (2) corpuscular radiation, due to the casting out of electrons from the atoms, and (3) fluorescent X-radiation, arising from the re-arrangement of electrons within the atoms subsequent to the emission of electrons (2). The fluorescent radiation, when analysed by a crystal, is seen to give a spectrum of lines,* characteristic of the atom from which it arises. Only those lines appear which have a wave-length longer than the shortest wave-length absorbed. When, therefore, the primary radiation is shortened in wave-length so as to approach and pass through a wave-length characteristic of the absorbing substance, not only will the absorption increase suddenly, but the corpuscular emission will also increase, and the substance will begin to emit this additional line (i.e. group of lines) in its spectrum of fluorescent radiations. The existence or non-existence of a spectral line can be finally settled by an examination of the spectrum as analysed by a crystal, the conditions being such that the spectral line should be excited. Strong evidence one way or the other can be obtained in a less direct manner, however. Barkla** has described experiments on the corpuscular radiations

* In reality the fluorescent radiation gives a number of groups of lines, the K, L, ...groups, but for convenience of description each group is called here simply a line.

**Barkla, Bakerian Lecture, 1916.

emitted by light elements, and his results go to show that the intensity of the corpuscular emission from light elements exhibits the same discontinuous character as the absorption by these elements, in the region of short wave-lengths. So far the evidence for the existence of a new series of characteristic radiations in this region (a J-series) was entirely positive and it was not until a search for J-lines, using the X-ray spectrometer, had failed*, and an attempt to reproduce the discontinuities of Barkla and White (under slightly different conditions) had given a negative result**, that any doubt was cast on this explanation of the discontinuities. The magnitude of the irregularities and the consistency with which they appeared with more than one observer completely ruled out any attempt to ascribe the results to experimental error. We naturally conclude that the discontinuities are real but that their appearance is conditional on some factor or factors. To find what these factors were was the object of the present series of experiments.

Source of X-rays.

A convenient source of X-rays of reasonable intensity suitable for experiments on the J-phenomena is that used by Barkla and White in their absorption experiments, viz. an ordinary X-ray tube, the softer components of the general

* Duane, Physical Review, April 1919.

** Hewlett, Physical Review, March 1921.

radiation being filtered out with sheets of copper or aluminium. The transmitted beam may then be sufficiently homogeneous for the purpose. By suitably modifying the potential applied to the tube and adjusting its conductivity a series of wave-lengths may be obtained which is more continuous and intense (though less homogeneous) than can be obtained by the use of characteristic radiations. Copper is a more efficient filter than aluminium on account of the smaller proportion of energy which it scatters, for the scattering is ineffective in filtering out the softer components. It has the disadvantage, however, that it superimposes on the transmitted beam a fairly intense K-radiation, which necessitates final filtering with aluminium. The amount of filtering which is practicable is limited by the intensity of the unfiltered radiation and by the sensitivity of the electroscopes. Too little filtering, on the other hand, may leave the transmitted radiation so heterogeneous, that the irregularities (which occur rather close together in some cases) may, in comparison experiments, flatten out, overlap and partially extinguish each other. The suitability of the Coolidge tube for this work was recognised. Used in conjunction with a "Mammoth" 16 in. Coil, and a "Sanax" Mercury Break, an intensity of several times that formerly obtained with an ordinary

gas-filled tube was got without difficulty, particularly in the case of the longer wave-lengths. A generous amount of filtering was possible, and the quality and intensity were under complete control, doubtful observations could be repeated and regions suspected of containing discontinuities could be explored in great detail. In all the experiments described below, a Coolidge tube of the broad-focus type with tungsten anticathode was used as source of X-rays, sheets of aluminium or copper or both being used as filters to produce the necessary degree of homogeneity.

Absorption Experiments.

When homogeneous X-rays traverse a thickness x of a substance, part of the radiation is transmitted unaffected, part is absorbed. The relation between the incident and transmitted intensities (I_0 and I , respectively) is given by the formula,

$$I = I_0 e^{-\mu x}, \qquad (1)$$

where μ is a constant for a given wave-length and a given substance. μ is called the "absorption-coefficient" and μ/ρ the "mass-absorption-coefficient" for the absorbing substance for the particular wave-length, ρ being the density.

When heterogeneous rays are used, μ is no longer

independent of x, for the less penetrating components of the beam are reduced more rapidly in intensity than the more penetrating components as the radiation traverses successive layers of the absorbing substance. The value of μ/ρ obtained by applying formula (1) will therefore have no definite meaning unless we stipulate that x will have a definite value. When the absorption-coefficients for two substances, as obtained by experiments on heterogeneous rays, are compared, the question arises, will the result bear any relation to that which we would obtain by using homogeneous radiation? We arrive at an answer to this question as follows.

We may write equation (1) in the form,

$$I = I_0 e^{-\bar{\mu} x} . e^{-\sigma x} = I_0 e^{-(\bar{\mu} + \sigma) x}$$

for there are two processes involved in absorption, true absorption (giving rise to corpuscular emission and fluorescent radiation) and pure scattering, each process producing an exponential decrease in the intensity of any given wave-length. We have therefore

$$\mu = \bar{\mu} + \sigma ,$$

where $\bar{\mu}$ is the "true" absorption coefficient, and σ is the scattering coefficient.

Let λ be the wave-length of one component of the heterogeneous beam, and let $J_0 \, d\lambda$ be the intensity of the radiation between λ and $\lambda + d\lambda$ before absorption.

Then the total intensity before absorption is given by

$$I_o = \int J_o d\lambda ,$$

and the total transmitted intensity by

$$I = \int J_o e^{-\mu x} d\lambda ,$$

and if τ is the value of the absorption - coefficient (really an average absorption-coefficient) obtained by applying the formula

$$I = I_o e^{-\tau x} ,$$

the relation between τ and the values of μ for the components of t the heterogeneous beam is contained in the equation

$$\int J_o e^{-\mu x} d\lambda = e^{-\tau x} \int J_o d\lambda . \qquad (3)$$

Writing $\bar{\mu} + \sigma$ for μ, and $\bar{\tau} + \sigma$ for τ, where $\bar{\tau}$ is that part of the average absorption-coefficient which is due to true absorption, (3) becomes

$$\int J_o e^{-(\bar{\mu} + \sigma)x} d\lambda = e^{-(\bar{\tau} + \sigma)x} \int J_o d\lambda . \qquad (4)$$

σ is known to be practically constant over the range of wave-lengths under consideration. Assuming it constant, the factor $e^{-\sigma x}$ will cancel out of the equation (4) and we obtain

$$\int J_o e^{-\bar{\mu} x} d\lambda = e^{-\bar{\tau} x} \int J_o d\lambda . \qquad (5)$$

For a second substance of thickness x_1 we get similarly

$$\int J_o e^{-\bar{\mu}_1 x_1} d\lambda = e^{-\bar{\tau}_1 x_1} \int J_o d\lambda . \qquad (6)$$

Our problem is to find values of x and x_1 such that the

the relation of $\bar{\tau}$ to $\bar{\tau}_1$ throughout our experiment will always be the same as the relation of $\bar{\mu}$ to $\bar{\mu}_1$. Now so long as the range of wave-lengths is removed from spectral lines of both substances, experiment has shown that $\bar{\mu}_1 = k\bar{\mu}$, where k is a constant. We require to choose our values of x and x_1, therefore, so that $\bar{\tau}_1 = k\bar{\tau}$. This relation is seen to be true if we take $x = kx_1$, for, remembering that $\tilde{\mu}_1 = k\tilde{\mu}$, the left-hand sides of (5) and (6) become identical, on substituting kx_1 for x and the right-hand sides will only be equal if $\bar{\tau}_1 = k\bar{\tau}$. It follows that our necessary condition is fulfilled if $\bar{\tau}x = \bar{\tau}_1 x_1$, or $\left(1-e^{-\bar{\tau}x}\right) = \left(1-e^{-\bar{\tau}_1 x_1}\right)$, that is, if the fraction of the total original intensity truly absorbed by the two substances is the same.

This precaution is important only when the ratio of "scattered" to "true" absorption is very different for the two substances compared, and the rays are distinctly heterogeneous. In the absorption experiments described here, the rays were found to be sufficiently homogeneous to allow considerable latitude in the percentage absorbed.

The mass-absorption-coefficients for silver, aluminium, paper and copper.

The mass-absorption-coefficients for silver, aluminium and paper were compared with those for copper over a range of wave-lengths which included those at which

appeared the J-discontinuities of Barkla and White. The X-ray tube, lead box etc. were arranged as shown in Fig.I.* Three electroscopes of the Wilson type were set up in front of apertures so that a pencil of radiation was directed into each. In reality a number of pencils were arranged to enter each electroscope so as to have the ionisation as uniformly distributed as possible. (Corpuscles emitted by air under the action of soft X-rays travel only a millimetre or two, and if the intensity of the X-rays were confined to a single pencil, the electric field would possibly be insufficiently strong to prevent recombination of ions). Sheets of copper and aluminium were placed against the apertures in the lead box at a, b and c on the side remote from the tube. These were increased or decreased in number so as to give as homogeneous an end-radiation as possible, consistent with a reasonable transmitted intensity. The amount of Lead L-radiation from the inside of the box containing the X-ray tube entering the electroscopes was reduced to a minimum by fixing lead cylindrical tubes behind the apertures, as shown in Fig.I. The quality of the radiation from the Coolidge tube was modified by suitable adjustments of the primary current in the induction-coil. The intensity could be increased by raising the temperature of the cathode, the resistance in the primary of the induction-coil being reduced at the same time to give the necessary

* See end of this paper.

additional energy. The relative rates of leak of the electroscopes when an equal filter was placed in front of each aperture was not quite constant when the wave-length of the radiation was altered, but this was taken into account. Absorption sheets of the substances under examination were added to the filters at b and c, respectively. Their thicknesses were adjusted to reduce the rates of leak of the corresponding electroscopes to about half, the third electroscope being used as a standard. The values of the mass-absorption coefficients for the two substances were calculated from equation (1). Tables I, II and III* contain the results of the experiment. The material of the filter and its thickness have been given for each observation and also the percentage absorbed by the absorbing sheet. When these results are plotted with μ/ρ for copper as abscissae, (Graph I.)**, we find no trace of discontinuities. An examination of the results will show that allowing a probable experimental error of only one-percent in the determination of μ/ρ all the deviations from a linear relationship between the mass-absorption-coefficients can be accounted for. The results obtained by Barkla and White for paper and aluminium are shown by broken lines in the same Graph. A comparison of the two sets of curves shows conclusively that whatever produced the discontinuities in the one set was certainly not present in the other, that under the

* See following sheets.

** See sheet following Table III.

TABLE I.

μ/ρ for Silver and Copper.

Filter	Per cent absd. by Ag	Per cent absd. by Cu	μ/ρ for Ag	μ/ρ for Cu
0·2 mm. of Cu and 6·5 mm. of Al.	55	51	13·65	4·35
	57	53	14·5	4·60
	59	55	15·1	4·81
	59	56	15·25	4·95
	60	57	15·6	5·04
	60	57	15·8	5·10
	61	57	16·05	5·17
	62	59	16·6	5·35
	62	58	16·8	5·32
	63	60	16·9	5·47
	63	59	17·2	5·46
	65	61	17·8	5·78
	65	62	18·2	5·94
	66	62	18·5	5·85
	70	67	20·45	6·75
	46	44	11·38	3·52
	48	46	12·07	3·78
	51	49	13·04	4·10

Table II.

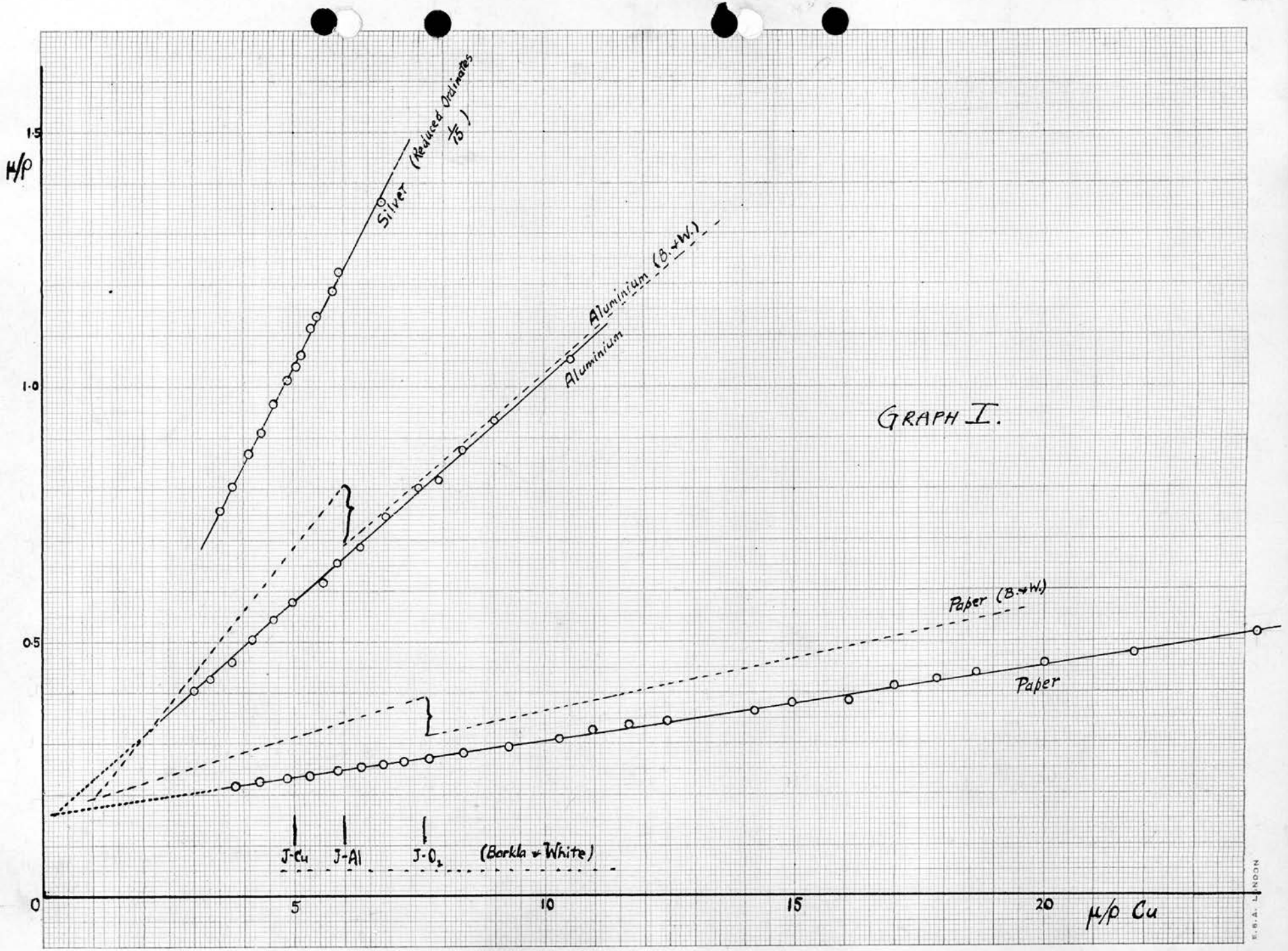
μ/ρ for Paper and Copper.

Filter in mm. of Al	Per cent absd. by Paper	Per cent absd. by Cu	μ/ρ for Paper	μ/ρ for Copper
22·8	46	48	0·218	3·82
··	47	50	0·226	4·30
··	48	56	0·232	4·85
··	49	58	0·239	5·30
18·0	50	62	0·247	5·86
16·3	51	65	0·253	6·32
··	52	68	0·260	6·77
··	52	64	0·265	7·18
13·0	53	56	0·270	7·69
··	49	42	0·282	8·37
10·7	40	32	0·294	9·28
··	41	35	0·310	10·28
9·8	44	37	0·328	10·95
7·4	44	38	0·330	11·68
6·5	46	40	0·346	12·45
··	47	45	0·365	14·20
··	49	46	0·381	14·95
··	49	50	0·385	16·10
··	49	49	0·412	17·00
4·15	50	53	0·426	17·86
··	48	54	0·440	18·65
··	45	57	0·457	20·00
··	46	60	0·476	21·80
3·25	60	64	0·511	24·27
··	61	66	0·544	26·05
··	62	68	0·562	27·20
Nil	54	69	0·583	28·20
3·25	60	72	0·604	30·45

Table III.

μ/ρ for Aluminium and Copper.

Filter	% Absorbed by Al.	% Absorbed by Cu.	μ/ρ Al.	μ/ρ Cu.
'28mm Cu ~~1'65~~ 16'3mm. Al	51	47	'402	3'00
	52	50	'426	3'33
	56	55	'460	3'78
'28mm. Cu 13'0mm Al	59	58	'504	4'175
	62	69	'542	4'60
'28mm Cu 9'8mm Al	64	65	'578	4'98
	66	69	'618	5'59
	52	52	'655	5'86
	70	74	'686	6'32
	57	58	'747	6'83
'28mm. Cu 6'5mm. Al	60	61	'802	7'49
'28mm. Cu 3'25mm. Al	52	48	'818	7'90
	58	58	'878	8'37
	56	53	'933	9'00
	60	59	1'052	10'52


H/ρ
1·5
1·0
0·5
0
Silver (Reduced Ordinates 1/15)
Aluminium (B. & W.)
Aluminium
Paper (B. & W.)
Paper
GRAPH I.
J-Cu
J-Al
J-O₂
(Borkla & White)
5
10
15
20
μ/ρ Cu
E. G. A. LINDON

conditions of experiment described in detail above, the J-discontinuities do not appear. The present experiments differ from those of Barkla and White in the following respects,

(1) a Coolidge tube was used, and not a gas-filled tube,

(2) the distance between anticathode and filters was about 48 cm., that is about twice or three times as great as in the other case,

(3) the anticathode was of tungsten (of platinum in the other),

(4) the filters were thicker, probably 2 to 4times as thick in the regions of the discontinuities, so that the end-radiation must have been more nearly homogeneous.

Experiments on Corpuscular Radiations.

It has already been stated that the energy absorbed when X-rays pass through a substance reappears in three forms, viz. as scattered radiation, corpuscular radiation and fluorescent radiation. It follows that corresponding to a discontinuity in absorption, there must be a discontinuity in one or more of the three secondary radiations. Under the conditions of experiment which obtained in Barkla's investigation, J-discontinuities appeared in both the absorptions and the corpuscular emissions. It seemed worth while to find out whether the corpuscular discontinuities would appear under the conditions of the absorption experiments described above, conditions which

eliminated the absorption discontinuities. If they did not appear, the conclusion arrived at as a result of the absorption experiments would be strengthened; if they did appear, there would be material for further investigation.

The intensity of the corpuscular radiation from a substance under the action of X-rays may be conveniently measured, if the substance is in the form of a gas, by finding the intensity of ionisation produced by the complete absorption of the corpuscles by the gas itself. If the substance is in the form of a solid, a plate of the substance may be exposed, in an atmosphere of hydrogen, to the action of the X-rays, when the ionisation of the hydrogen will be produced almost entirely (over 99 per cent, probably) by the corpuscles sent out from the plate. The intensity of ionisation of the hydrogen will give a kind of measure of the intensity of the corpuscular emission from the substance of the plate. This method of measurement will evidently be good enough for the location of discontinuities. These two methods of studying the corpuscular emissions from substances were applied to various substances. The ionisation-chamber used in every case was the same. It consisted of a brass cylindrical tube, 14 cm. long and 10 cm. in diameter. The inside of this tube was covered with aluminium 0·1 mm. thick, and aluminium plates 1·5 mm.

thick were fitted to the ends. The electrode consisted of a straight piece of aluminium wire lying along the axis of the tube and supported there by a wire running at right angles from its centre through the side of the tube, from which it was insulated by a plug of ebonite. This type of electrode was suitable for cases where the gas was directly ionised by the X-ray, which, entering the chamber in the form of one or more pencils parallel to the axis, produced a cloud of ions much longer than its breadth, so that the lateral field given by the axial electrode would rapidly separate positive stream from negative. In the case of hydrogen, which is ionised almost entirely by the corpuscles sent out from the plates at the ends of the chamber, the electrode used was a circle of aluminium wire covered with a mesh of fine cotton thread and fixed with its plane at right angles to the axis. Such an electrode would be more effective in separating the ions due to the corpuscles leaving the ends with low velocities, especially, as in these experiments, when the cross-section of the X-ray was considerable. The ionisation-current was measured in all cases by means of a Wilson electroscope of the cubical box type, the connection between the electrodes of the two instruments being made as short as possible to reduce the capacity, for the electroscope of this form can only be considered sensitive when the capacity of the electrode has a very small value.

When soft X-rays are used, the ionisation of a gas such as SO_2 in a chamber of this size may be taken as a fairly accurate measure of the corpuscular energy emitted by the gas. Probably no corpuscles will reach the sides of the chamber, if the pencil of X-radiation is not abnormally wide, for the maximum velocity of emission possible with a given wave-length is a function of wave-length only (the maximum kinetic energy of a corpuscle is hn, where h is Planck's constant and n is the frquency of the X-ray) and the range of corpuscles in gases at atmospheric pressure is of the order just a millimeter or two when the radiation is soft. The energy lost by corpuscles striking the ends of the chamber will be a negligible fraction of the total ionisation energy, and that gained by corpuscles sent out by the ends of the chamber will be a quantity of the same order and therefore negligible. When we come to hard X-rays, on the other hand, the range of corpuscles is now of the order of centimeters, ~~and~~ ~~ially in hydrog~~ hydrogen is much more transparent to high velocity corpuscles than other gases. With X-ray of decreasing wave-length, a point will be reached when the speeds of the corpuscles will be great enough to carry a percentage of their number to the sides of the chamber before their energy has been completely expended in ionisation, a percentage of energy will therefore fail

to be recorded and the deficiency will become more and more pronounced as the wave-length decreases. The loss and gain of corpuscles at the ends of the chamber, on the other hand, is present at all wave-lengths and may begin to produce an appreciable effect long before the loss at the sides has become important. The net loss or gain at the ends depends normally on the difference in average atomic weight between the gas and the material of the ends. (If a spectral line of one of the elements contained in the gas or the ends is included in the range of wave-lengths there will obviously be a sudden change in the net loss or gain when this is excited.) If the gas and the ends were composed of the same substance the net loss or gain would be nil, for we have no reason to suppose that the motion of corpuscles should depend on anything but their speed, the substance passed through and the number of molecules which the corpuscles encounter. The corpuscles do not recognise any essential difference between a gas and a solid so that at the boundary between solid and gas at the ends of the chamber, solid and gas having the same molecular constitution, as many corpuscles will pass in one direction as in the other. In practice it is usually impossible to get the same substance in the two states in an ionisation-chamber, but it is generally possible to approximate to this ideal arrangement by covering

the ends with some substance whose "average" atomic-weight is very near to that of the gas, e.g. in the case of air, paper may be used, and, in the case of SO_2, aluminium. The thickness of the paper or aluminium must be sufficient to ensure the full corpuscular emission.

The facts just mentioned must be taken into account when irregularities in comparative corpuscular experiments appear. For example, if a light gas (air, say) is being compared with a heavy one (SO_2, say) the two gases being caused to fill the same ionisation-chamber alternately, the ionisation of each gas being measured in terms of the leak of a standard electroscope, and if the radiation is gradually decreased in wave-length, three irregularities should appear. The loss at the sides should take effect with air before SO_2 for the range of corpuscles is greater in the former case. The experimental values of the ratio

$$\frac{\text{Ionisation of } SO_2}{\text{Ionisation of Air}}$$

will therefore be expected to begin to rise abnormally, and later to begin to rise less rapidly (and perhaps to cease rising) when the SO_2-corpuscles begin to reach the sides of the chamber. The third irregularity will appear on account of the fact that the lighter gas

is more adequately compensated at the ends than the heavier gas, so that as soon as the net loss or gain at the ends begins to be appreciable in one of the gases, the ratio

$$\frac{\text{Ionisation of } SO_2}{\text{Ionisation of Air}}$$

will begin to decrease abnormally. The latter effect would be expected to occur first, for a reason already stated, that the end effect is there from the beginning, while the effect at the sides does not occur at all until the velocity of the corpuscles is sufficient to carry some of their number as far as the sides of the chamber. To prevent any mistake in the interpretation of kinks in the resulting curve, it is usual to take "pressure-ionisation" curves, one on each side of the kink, that is, the variation of ionisation with pressure is observed before and after the discontinuity. Such curves show ~~at once~~ the percentage gain or loss at the boundary and it can be decided at once whether the kink is to be attributed to boundary effects or to a change in the corpuscular emission. This procedure was adopted in all cases where irregularities presented any difficulty in interpretation.

Fig.I. gives the arrangement of the apparatus for the ionisation experiments. The ionisation chamber on the left was normally not in use. It was used later to make a direct comparison between pairs of

substances where an indirect comparison in terms of a standard electroscope was not considered sufficiently conclusive.

Ionisation of Sulphur Dioxide and Ethyl Bromide.

The electroscopes and the ionisation-chamber were provided back and front with aluminium sheets which were covered again with 5 sheets of filter paper on the sides facing the gas which was to be ionised. A separate experiment showed this number to be sufficient to prevent corpuscles from the aluminium penetrating into the gas even when the radiation was very hard. When the ionisation-chamber was filled with air at atmospheric pressure, the relative ionisations in air-electroscope and chamber were found to be constant to about 1% or so. The treatment of ionisations in the electroscope as if they had been measured in the ionisation-chamber was therefore considered justified, to this degree of accuracy.

The paper was now removed from the ends of the ionisation-chamber and the aluminium exposed, so that the SO_2 about to be introduced would be as nearly as possible compensated for end effects. The gas being introduced up to atmospheric pressure, the relative ionisations in electroscope and chamber were found over a considerable range of wave-lengths.

As it was certain that the conditions for the J-discontinuities in absorption were absent in the absorption experiments described above, it seemed, a priori, that the J-discontinuities in corpuscular radiation would not appear if the same conditions were exactly reproduced. It was on this account decided to modify these conditions in one particular way to see whether this change would effect the appearance of the J-discontinuity. The radiation in this experiment was to be much more heterogeneous, the filtering to be reduced as nearly as possible to that used in the experiments of Barkla which gave decided discontinuities. The following difficulties were met with in making the observations. Very large ions seemed to be formed in the SO_2 by the action of the X-ray, causing a slow rate of leak (amounting to 2 or 3 per cent of the total leak, sometimes) after the X-ray was cut off, the leak lasting for a few minutes. This in itself made individual observations unreliable to a per cent or two. Heterogeneous beams giving the same value for μ/ρ may differ very much in quality, and if the relation which is being measured is not a linear one, that is, if it is represented by a curve, then, the more heterogeneous the radiation is, the greater will the observation be in error in the direction of concave side of the curve. A complete series of observations could not be taken at one sitting so that

the readings taken at one time could not be expected to be exactly comparable with those taken at another. In spite of these sources of error, the observations when plotted fall fairly well on a smooth curve. (See Graphs II and V, Curves I, and see also Table IV for particulars of the observations). The undulations which appear might quite reasonably be taken to lie within the region of experimental error, but a repetition of the experiment with paper instead of aluminium at the ends of the ionisation-chamber seemed to show that the undulations were real. (See Graphs II and V, Curves II, and see also Table V for particulars of the observations). Before interpreting the results it is necessary to explain how the final ratios of the ionisations of air and SO_2 were arrived at, and to explain the purpose of re-plotting these ratios against the frequencies of the exciting radiation.

One electroscope was used as a standard for measuring the intensity of the radiation which entered the ionisation-chamber. The second electroscope, whose rate of leak relative to the first was known (it varied a little with wave-length, but this was allowed for), was used for the determination of μ/ρ for the radiation, the additional thickness of aluminium placed in front of this electroscope being adjusted to reduce its normal rate of leak to as nearly 50% as possible. The readings of the standard electroscope were also taken to be proportional

* See following pages.

TABLE IV.

Relative Ionisation of SO_2 and Air.

(SO_2 chamber 14cm. long, 10cm. diam., ends of Al).
(Air electroscope 9cm. long, ends of paper. Windows 1.5 mm Al.)
(Radiation fairly heterogeneous.)

Filter	μ/ρ Al	% Absorbed by Al	SO_2 Air	SO_2 Air (Corrected for Absorption)	
8'0mm. Al	'540	38	1·251	1'262	Arbitrary Scale.
4'75	'607	41	1'262	1'274	
6'4	'670	45	1'185	1'200	
6'4	'718	47	1'198	1'214	
6'4	'857	53	1'198	1'219	
4'0	1'038	51	1'142	1'167	
4'0	1'14	55	1'150	1'176	
3'25	1'32	49	1'145	1'178	
3'25	1'66	34	1'155	1'198	
3'25	1'78	36	1'138	1'181	
2'4	1'97	39	1'116	1'166	
1'5	2'23	43	1'069	1'121	
1'5	2'85	51	1'011	1'078	
1'2	3'33	57	1'011	1'095	
1'0	3'52	58	'978	1'064	
1'0	4'10	64	'958	1'066	
1'0	4'30	66	'956	1'070	

TABLE V.

Relative Ionisations of SO_2 and Air.

Al Filter Thickness	μ/ρ Al	% Absd. by Al	SO_2 / Air	Ratios adjusted for Comparison	Ratios corrected for Absorption.
9·8 mm.	0·60	41	·923	'923	·932
" "	0·727	47	·978	·978	·991
" "	0·92	55	·994	·994	1·012
3·25 mm	1·53	54	1·007	1·007	1·041
Nil.	4·45	69	·864	·847	·966
"	4·0	65	·870	·853	·951
9·8 mm.	0·792	50	1·005	·986	1·001
1·5 mm.	2·22	44	·948	·929	·976
"	2·42	47	·930	·912	·962
"	2·60	49	·927	·908	·967
Nil.	4·1	41	·870	·853	·955
3·25 mm.	1·48	53	·971	1·009	1·041
"	1·63	56	·957	·995	1·031
"	1·81	60	·956	·994	1·034
"	1·64	56	·967	1·005	1·041
4·75 mm.	1·13	44	·973	1·011	1·036
"	1·24	47	·975	1·014	1·043
"	1·36	50	·975	1·014	1·044

Deduct 2%. (applies to the 1·005 row)

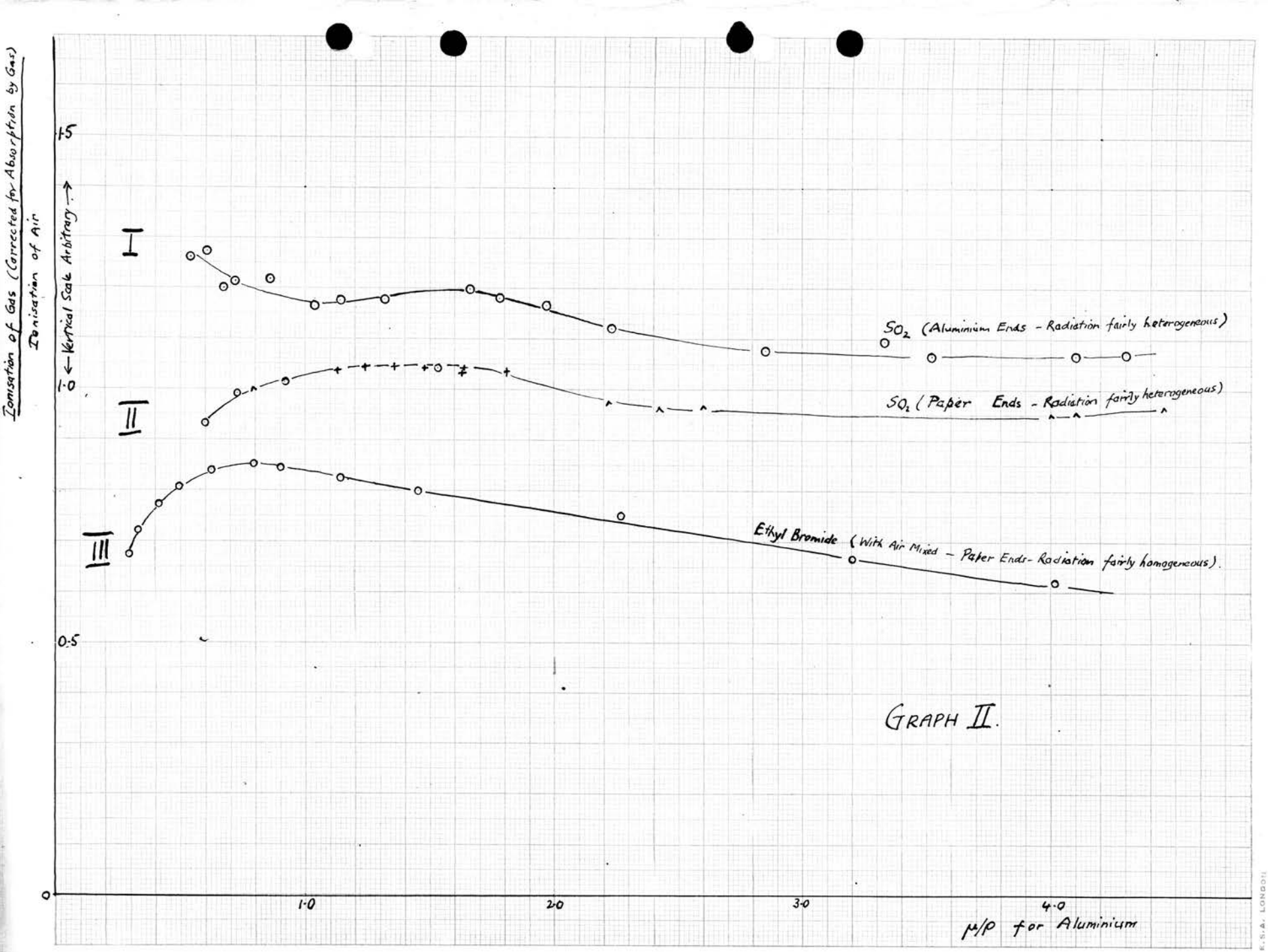
Add 4%. (applies to the 1·64 row)

SO_2 -- Cylindrical ionisation chamber, 14 cm. long, 10 cm. diameter, ends of paper. The last column corrects for the falling off of the intensity of the primary intensity as the radiation passes through the SO_2.

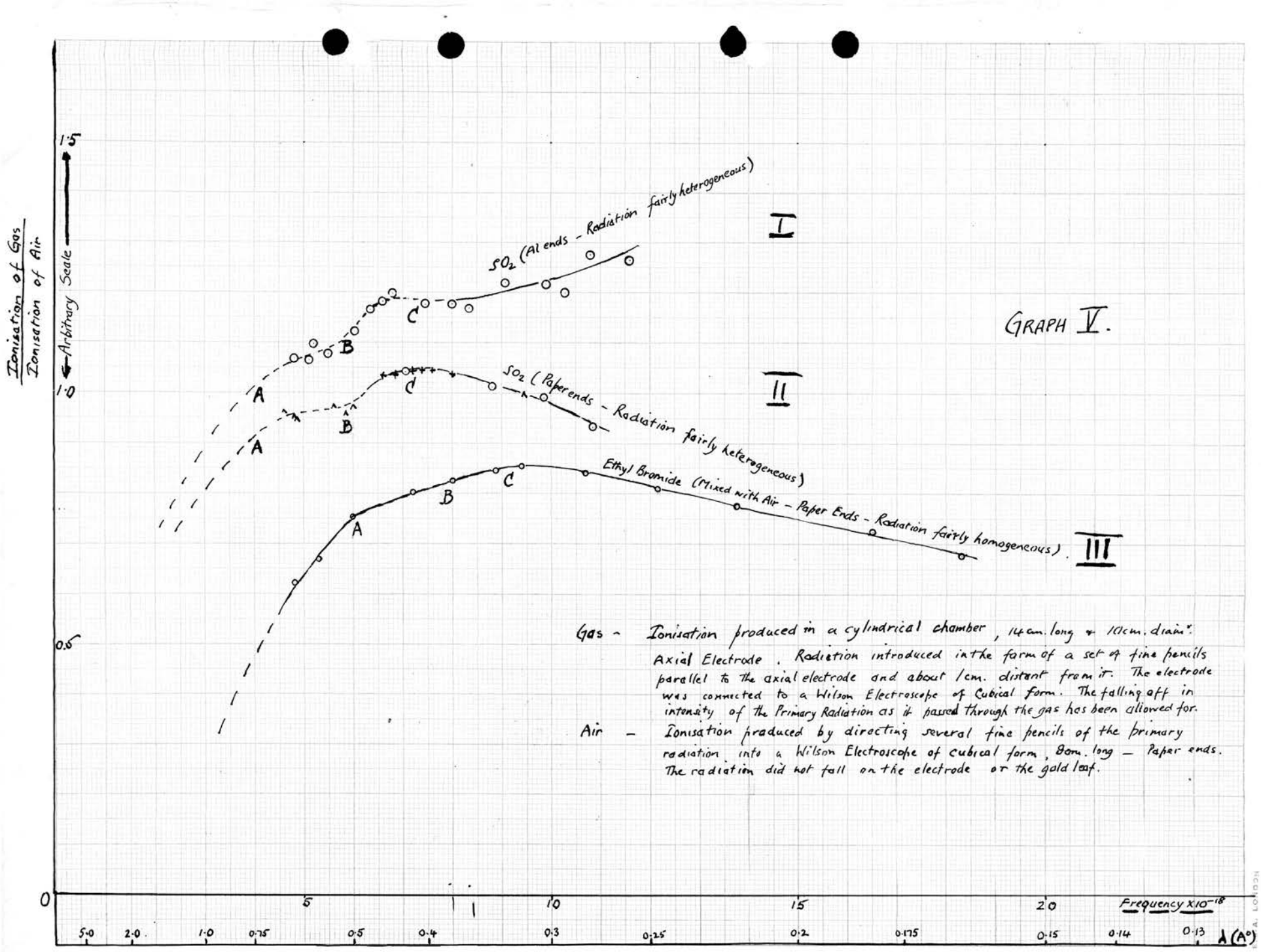
Air -- Ionisation measured by directing several fine pencils of radiation into a cubical electroscope, 9 cm. long, ends of paper.

The primary was fairly heterogeneous, as seen by the thickness of the filters used,

The ratios of the ionisations are given on an arbitrary scale. The three groups of observations were taken at different times and the ratios obtained (col. 4) have been adjusted for comparison with each other (col. 5). The factors required have been obtained by comparing observations where two groups overlap.



GRAPH II.



GRAPH V.

Gas - Ionisation produced in a cylindrical chamber, 14 cm. long × 10 cm. diam.: Axial Electrode. Radiation introduced in the form of a set of fine pencils parallel to the axial electrode and about 1 cm. distant from it. The electrode was connected to a Wilson Electroscope of Cubical form. The falling off in intensity of the Primary Radiation as it passed through the gas has been allowed for.

Air - Ionisation produced by directing several fine pencils of the primary radiation into a Wilson Electroscope of cubical form, 8 cm. long - Paper ends. The radiation did not fall on the electrode or the gold leaf.

to those which would have been obtained with the SO_2 chamber filled with air and with the ends covered with filter-paper. (This, as already mentioned, was justified to about one per cent accuracy by a preliminary experiment). A correction had to be made for the fact that, although the radiation entering the SO_2 chamber was presumably identical with that entering the standard electroscope, by the time the radiation had penetrated to the far end of the chambers, the intensity had fallen off considerably more in the case of SO_2 than in the case of air, owing to the comparatively large absorption-coefficient of the former gas. The correction required in the case of each gas is one which will convert $\int_o^l \mu I dl$ (the actual absorption by a layer of gas of thickness l, and absorption- coefficient μ, where I is the intensity entering an element dl) into $\int_o^l \mu I_o dl$ (the absorption by the layer when the intensity entering each element is the same as that entering the first element = I_o). Since $I = I_o e^{-\mu l}$, the correcting factor required is

$$\frac{\int_o^l \mu I_o dl}{\int_o^l \mu I_o e^{-\mu l} dl}$$

which reduces at once to

$$\frac{\mu l}{1 - e^{-\mu l}} .$$

The value of this factor in the case of air is so nearly unity ~~in the case of air~~, that the correction need only be applied in the case of SO_2. Using the values of μ for SO_2 found by Barkla and Collier* for characteristic radiations and plotting the values for the correction factor against the values of μ/ρ for Al for these characteristic radiations, a graph was drawn of correction factor against μ/ρ for Al, and by interpolation in this graph the correction for the observations were determined. The largest correction required was little more than 10%, so that this rough method for its determination seemed to be quite good enough.

The use of the μ/ρ scale as abscissae is not very satisfactory when the observations are carried into the region of hard X-rays. X-ray phenomena depend almost entirely on energy and as μ/ρ is nearly proportional to $(\text{wave-length})^3$, that is, to the inverse cube of the frequency, or the inverse cube of the energy quantum of the radiation, the energy quantum must increase very rapidly as we approach the origin along an absorption-coefficient axis. Changes which are very gradual from an energy point of view will appear to come suddenly and perhaps discontinuously. This would be misleading. The conversion of absorptions to frequencies seemed to be desirable before any attempt

* Barkla and Collier, P.M. 1912.

was made to interpret irregularities in the curves. A further argument in favour of the frequency point of view is that the end effects and side effects mentioned previously are ~~determined~~ by changes in the velocity of emission of the corpuscles, and that again depends on $\nu - \nu_0$, where ν is the frequency of the incident radiation and ν_0 is the frequency corresponding to the level from which the corpuscles is removed. (The truth of this statement is still somewhat in doubt, see Barkla and Dallas, P.M. 1923.). In the case of a second substance the irregularities will depend on $\nu - \nu'_0$, where ν'_0 is the frequency corresponding to the energy level from which the corpuscles emerge from the second substance. Peculiarities in the shape of the curves arising on account of velocities, other things being equal, will appear in both curves in the same way but displaced to the right in the second case by $\nu'_0 - \nu_0$. If the curves were plotted with μ/ρ as abscissae, the relation of the peculiarities would not be so apparent. Examples of this fact will appear when the curves are interpreted.

With regard to the values of Ionisation of SO_2 / Ionisation of Air, the absolute values were not determined accurately, the purpose of the experiment being to discover irregularities. The values have therefore been plotted on an arbitrary scale. In the

case of Curve II, the observations were taken in three groups on different days, and a certain amount of adjustment was necessary to make the readings comparable with one another, amounting to 2% in one group and 4% in the other. These factors were obtained by comparing observations where the groups overlapped. The points on the graphs belonging to the three groups have been marked with crosses, circles and arrow-heads, respectively.

The J-discontinuities obtained by Barkla in the comparison of the ionisation of SO_2 and Air were of the order of 50% at least; with shortening wave-length the ratio Ion. of SO_2/Ion. of Air was found in his experiments to decrease suddenly (interpreted as due to a large increase in the corpuscular radiation from air) followed by a sudden increase ~~to the normal ratio~~ (interpreted as due to the appearance of the corresponding increase in the corpuscular intensity from SO_2). No discontinuity of this order appears in the present experiments. The humps at B,B (Graph V, Curves I and II) are of this character but indicate irregularities of the order of 2 to 3 per cent only. As the experimental error is of this order, more careful experiment would be necessary to decide whether they are real or not. The two curves begin to differ from one another at C,C, diverging from one another as we go to the right. As the two experiments differed only in that the ends of the

~~ionisation chamber~~

ionisation-chamber were of aluminium and paper respectively, the difference is naturally attributed to the difference in compensation for corpuscular loss at the ends. If this conclusion is the correct one, and there seems to be no other possible, we have here an indication that high velocity corpuscles (corresponding to about wave-length 0·3) are abnormally penetrating. For, using Whiddington's results to find an approximate estimate for the length of the track, we have

$$V_0^4 = ad$$

where V_0 is the velocity of emission, d is the length of the track and a is a constant for a given substance (2×10^{40} for air). For wave-length 0·3 A^0, the velocity of a corpuscle carrying a whole quantum of energy is given by

$$\tfrac{1}{2} mv^2 = h\nu, \text{ or } v^2 = \frac{2hc}{m\lambda} = \text{(app.) } 1\cdot46\times10^{20}. \quad \text{C.G.S.}$$

The length of track in air is therefore

$$d = v^4 / a = (2\cdot13\times10^{40}) / (2\times10^{40}) \text{ cm.}$$

$$= 1\cdot06 \text{ cm. (Atmospheric pressure).}$$

The density of SO_2 is fully twice that of air, so that the maximum range in SO_2 would not be greater than 0·5 cm. The ionisation-chamber was 14 cm. long, so that not more than three or four per cent would reach the ends, even if all the corpuscles moved in the direction of and parallel to the

X-ray beam and were undeflected. According to Hull and Rice, the wave-length 0·3 has μ/ρ for Cu = 3·72, and Graph I in this paper gives the corresponding μ/ρ for Al = 0·47. Extrapolation in Graph II, Curve II gives a net loss at the ends of about 15 per cent!

The rise in Curve I, Graph V to the right of C indicates that the Al at the ends over-compensates the SO_2 for loss of corpuscles.

It was concluded from this experiment that the J-discontinuity was absent, which eliminated one of the possibilities, namely, that the homogeneity of the radiation in the absorption experiments described above was the reason for the non-appearance of the discontinuities. It was decided to use as homogeneous rays as possible in future as observations with well filtered radiation seemed to give more consistent results.

The above experiment was repeated with Ethyl Bromide in place of SO_2, the ends of the chamber being of paper. The radiation was filtered as much as possible, consistent with a reasonable rate of leak in the electroscopes. The vapour-pressure of this liquid is of the order of about 20 cm. of mercury at ordinary temperatures. To prevent the formation of large ions, which would occur in a nearly saturated vapour under the action of X-rays, the vapour was introduced into the evacuated chamber up

to a pressure of only a centimeter or two of mercury. To prevent excessive loss of corpuscles at the boundary of the chamber, which would result from the low pressure of the gas, the pressure was brought up to atmospheric b by introducing air. The ionisation of a mixture of gases is a complex matter, but for the present purpose, the location of discontinuities, this was considered unimportant. It was found that the mixture was ionised, for a given intensity of X-ray, to very nearly the same extent as SO_2 at atmospheric pressure. It was therefore assumed that the absorption-coefficient of the mixture was nearly the same as that of SO_2, and corrections to the ratio

$$\frac{\text{Ionisation of Ethyl Bromide}}{\text{Ionisation of Air}}$$

on account of absorption by the gas were applied as if the gas were SO_2. Details of the observations are given in Table VI,* and the results are plotted in Graphs II and V.** (Curves III). We find a strong similarity between Curves II and III when the ratios are plotted against frequency (Graph V.).

An approximation to the theoretical shape of these curves is obtained in this way. The true-absorptions of substances, as distinguished from the scattered absorption, are known from experiment to be very nearly if not accurately proportional to each other in regions which are not close to a spectral line of

* See next sheet.

** See facing page 21.

TABLE VI.

Relative Ionisation of Ethyl Bromide and Air.

(Eth.Br. chamber 14cm. long, 10cm. diam., ends of paper, gas to a few cm. of Mercury, and air added up to atmospheric pressure, rate of ionisation about same as for SO_2.

Air electroscope 9cm. long, ends of paper. Windows 1'5mm. Al. Radiation fairly homogeneous.)

Filter	μ/ρ Al	% Absorbed by Al	Eth.Br. / Air	Eth.Br. / Air (Corrected for Absorption.)	
29'3mm. Al	'295	54	'673	'676	
22'8	'328	51	'716	'721	
16'3	'410	51	'766	'774	
13'0	'495	50	'798	'807	
9'8	'622	50	'830	'840	Arbitrary
8'0	'795	51	'839	'853	Scale.
6'5	'90	55	'826	'844	
4'65	1'14	52	'804	'824	
3'25	1'45	53	'775	'800	
1'40	2'27	43	'721	'752	
0'47	3'20	55	'627	'667	
0'00	4'02	43	'569	'620	

either of the substances. Assuming the relation is an accurate one, the numbers of quanta absorbed will also be proportional. If one corpuscle is emitted for every quantum absorbed, the numbers of corpuscles must also be proportional. For simplicity let us confine our attention to the K-absorption only. The kinetic energy of an ejected corpuscle will be $h(\nu - \nu_K)$, where ν_K is the frequency corresponding to the K level from which the corpuscle has been ejected. The ratio of the total corpuscular energies from two substances will therefore be proportional to $(\nu - \nu_{K_1}) / (\nu - \nu_{K_2})$. If the ionisation is proportional to the corpuscular energy absorbed, we may now write,

$$(R) = \frac{\text{Ionisation of Gas}}{\text{Ionisation of Air}} = k \cdot \frac{\nu - \nu_{K_1}}{\nu - \nu_{K_2}} ,$$

where ν_{K_1} is the K level frequency for the Gas

and ν_{K_2} .... Air,

and k is a constant.

ν_{K_2} may be neglected in comparison with ν, so that when the K ionisation of bromine is compared with that of air, and the ratio (R) is plotted against ν, the resulting curve is given by

$$(R) = k\left(1 - \frac{\nu_{K_1}}{\nu}\right)$$

The experimental curves obtained for SO_2 and Ethyl Bromide are of this form on the left of C (Graph V). There are L-corpuscles as well as K, of course, but the latter

will predominate in number since the K-absorption is so much greater; they will also predominate in total energy when ν is much greater than ν_{K_1}. The theoretical curve cuts the frequency axis at $\nu = \nu_{K_1}$, but the experimental curve will, with decreasing frequency, be determined more and more by the L corpuscular energy so that the curve will be inflected towards the origin. The observations did not include a wide enough range to show this. If the curve III (Graph ν) were displaced about 2 cm. to the left, it would be seen to resemble Curve II. very strongly. Now the value of ν_K for bromine is approximately $3{\cdot}5 \times 10^{18}$ and that for sulphur about $0{\cdot}65 \times 10^{18}$, giving a difference of $2{\cdot}85 \times 10^{18}$ which is 2·85 cm. on the scale of the graph. The difference between 2 cm. and 2·85 cm. is to be accounted for by the fact that we have L as well as K corpuscles, and we are not dealing with the pure elements, the bromine, in particular, being combined with lighter elements and also mixed with air. The dip to the right of C in Curve III evidently corresponds to that in Curve II, and is to be attributed to loss of corpuscles at the ends. A, B and C are points on the three curves which on the above interpretation correspond as regards corpuscle velocity. It is therefore to be expected that, since the two gases are about equally dense, the end-effect should become appreciable at points where the corpuscle-velocities are about

alike; in this case the points are C and C. The Curve III has been drawn with a flat part at A to C. A smooth curve might easily have been drawn among the points, and the deviations covered by experimental error. The curve as drawn, however, fits the points better and the irregularity seems to be related to the irregularities at B, B in the other two curves. If that were so the explanation would be concerned with the corpuscle velocity, but an explanation on this ground is difficult to find. If the irregularity in Curve III is real, it seems more probable that it is due to the fact that we have L-corpuscles with nearly the full energy of the quantum as well as the slower K-corpuscles. The former group begin to lose energy at the ends earlier than the latter as the frequency is increased, so that we get a double fall. In other words, we have resolved the L from the K corpuscles.

An ionisation-pressure curve was found for Ethyl Bromide for radiation of μ/ρ Al = 0·35, and this showed that about 10 per cent of the ionisation was lost at the ends. The Curve III shows a drop of ~~about~~ at least 15 per cent at this point. This may be considered to be agreement within the limit of error of experiment. It should be remembered, however, that the falling-off in the ratio (Ionisation of SO_2)/(Ionisation of Air) with shortening wave-length in this region was also found to be more rapid than a consideration of end-losses would have led us to expect. We may conclude, therefore, that there is at least a possibility that the falling-off in the ratios may be partially accounted for by an abnormal and gradual increase

in the intensity of the corpuscular emission from air, with shortening wave-length, a conclusion to which we are led by considering the results of another set of experiments about to be described. This abnormal emission of corpuscles is in accord with the quantum-theory of scattering advanced by A.H. Compton,* and with the observation by C.T.R.Wilson** of fish-tracks in his recent cloud-experiments. The proportion of "scattered" absorption to true absorption in the case of air is much greater than in the case of the other two gases; consequently a corpuscular emission associated with scattering would produce a correspondingly greater effect in the case of air on the total intensity of the corpuscular emission, thus reducing the ratio (Ionisation of Gas)/(Ionisation of Air) as the"scattered" emission became more intense, that is, as the wave-length diminished.

To convert values of μ/ρ for Al to frequencies, it was not considered advisable to use experimental values of the absorption-coefficients of wave-lengths, for these contain experimental errors of appreciable magnitude, judging by the differences between the results of different observers. The probability is that apart from regions which contain spectral lines, there exists a smooth relationship between wave-length and absorption-coefficient. An approximate empirical formula has been founded on the experimental values determined up to a recent date,

$$\mu/\rho = 0{\cdot}2 + 0{\cdot}0195\, z^{2{\cdot}58}\, \lambda^{2{\cdot}8} \quad ***$$

where z is the atomic-number of the absorbing substance, and λ is the wave-length. This formula was considered sufficiently accurate for the purpose of converting from absorption-coefficients to frequencies, since we are

* A.H. Compton, Phys. Rev., 1923.
** C.T.R. Wilson, P.R.S., 1923.
*** Interpolation formula of Kossel, Sieghahn and Glocker.

at present searching for discontinuities only. Points where irregularities appear can have their true frequency or wave-length determined afterwards, if necessary, from the experimental values of the absorption coefficients of definite wave-lengths.

Corpuscular radiation from plates.

The direct ionisation of Hydrogen by X-rays is known to be very small, and when X-rays fall on a plate in an atmosphere of this gas, the resulting ionisation of the hydrogen may be taken as entirely due to the corpuscles emitted by the plate. As a means of measuring the corpuscular energy emitted per unit volume of the substance of the plate this method is not suitable, for we have no very accurate knowledge of the law of absorption of high-speed corpuscles by matter. On the other hand, if we can obtain by another method the corpuscular intensity emitted per unit volume of substance for a given intensity and quality of X-ray, we may learn something of the law of absorption of corpuscles by the substance, from the energy leaving the surface of the substance (as measured by ionisation of hydrogen) for different wave-lengths of X-ray.

A serious difficulty arises in this method of measuring the corpuscular energy from plates when the radiation is at all hard, for the hydrogen is very transparent to corpuscles, as compared to other

gases. Pressure-ionisation curves showed that corpuscles were getting across the ionisation-chamber when the radiation was as soft as 3·0 μ/ρ Al, and this is very near to the soft end of the range of wave-lengths used.

The hydrogen was obtained from a Kipp's apparatus charged with zinc and dilute sulphuric acid. These substances were fairly pure, for the action of the zinc on the acid was very slow. The gas was passed through caustic potash, calcium chloride and cotton wool, to exclude sulphuric acid spray, moisture and dust particles, but no other precautions were taken to exclude impurities. The substances experimented on were (1) seccotine (which was to be used to bind powders together, and had therefore to be tested separately), (2) paper (to represent carbon and oxygen), (3) aluminium, (4) copper, (5) lead. As before, back and front of the ionisation-chamber were of Aluminium 1·5 mm. thick, the length of the chamber was 14 cm. and the diameter 10 cm., and the inside curved surface was covered with Al 0·1 mm. thick. In the case of copper, paper and seccotine, these materials were fixed to the insides of both of the Al ends, the thickness in each case being sufficient to give the full corpuscular effect even with the hardest rays. For the sake of uniformity a sheet of copper of equal thickness was added to the filters in front of the electroscopes

when that substance was being tested. In the case of lead, only the far end of the chamber could be covered with this element on account of its large absorption-coefficient. The front end of the chamber in this case was covered with paper. By far the larger portion of the ionisation would be produced by corpuscles from the lead and for our present purpose the paper effect was considered negligible. By having plates at both ends of the chamber (excepting lead) irregularities which might arise from the uneven distribution of the corpuscular radiation, demonstrated by C.T.R.Wilson in his cloud experiments, were avoided. As a matter of fact lead, which was fixed to the back of the chamber only, gave a curve with exactly the same features as the other curves, so that the precaution of having sheets at both ends would seem to be superfluous.

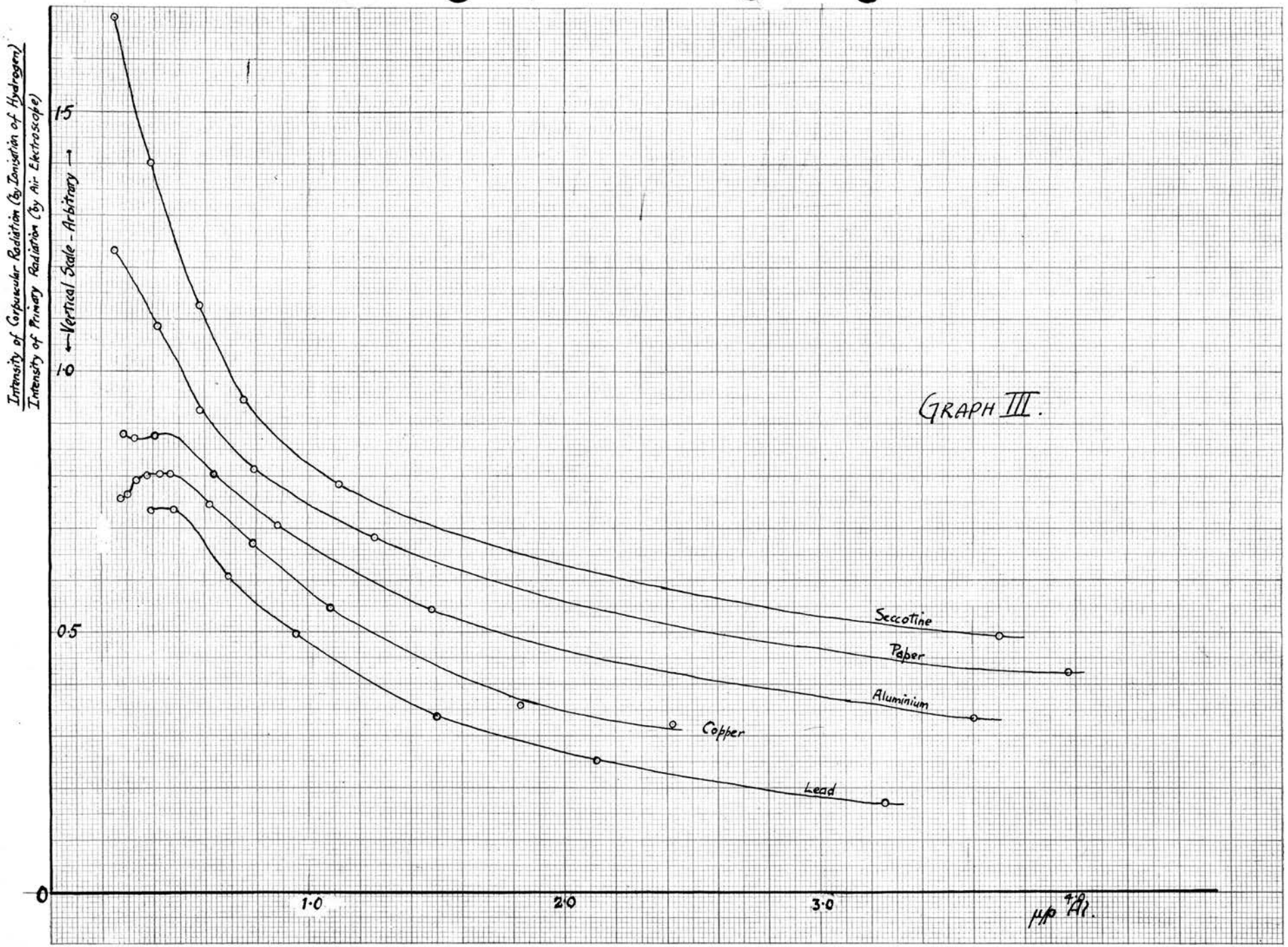
The apparatus was arranged exactly as in the previous experiment on gases. The ratio of Ionisation of H_2 to Ionisation of Air (as measured by air electroscope) was found for a range of wave-lengths which included the region of the J-discontinuities. The details of the observations are given in Table VII and the ratios are plotted against μ/ρ Al and frequency respectively in Graphs III and IV. The ratios of the ionisations are given on an arbitrary scale, absolute values being of little importance for our present purpose.

TABLE VII.

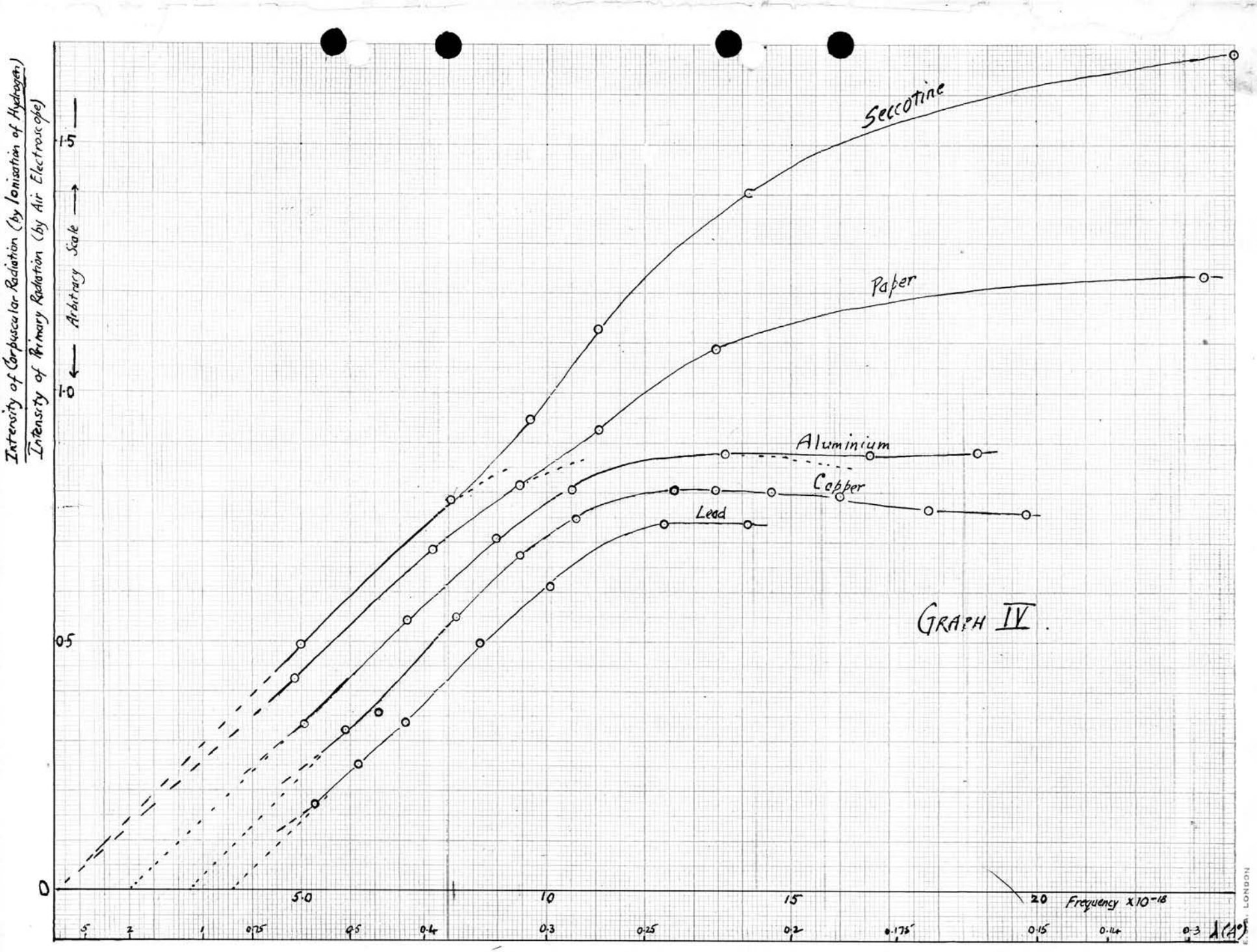
Relative Ionisation of Hydrogen (by plates) and Air.

(Hydrogen chamber 14cm. long, 10cm. diam., ends as tabulated, pressure atmospheric, window 1'5mm. Al.
Air electroscope 9cm. long, ends of paper, window 1'5mm. Al.
Radiation fairly homogeneous.)

Filter	μ/ρ Al	H_2/Air Celloidine both ends of H_2	H_2/Air Paper at both ends of H_2	H_2/Air Aluminium both ends of H_2	H_2/Air Copper both ends of H_2	H_2/Air Lead at back Paper at front of H_2
29'3mm. Al	'242	1'680	...	...	...	...
" "	'244	...	1'232	...	...	...
" "	'275	...	...	...	'758	...
" "	'284	...	...	'880	...	...
" "	'300	...	...	...	'765	...
22'8mm. Al	'328	...	...	'872	...	...
" "	'336	...	...	...	'792	...
19'6mm. Al	'376	...	...	...	'801	...
16'3mm. Al	'389	1'402	...	...	...	...
22'8mm. Al	'392	...	...	...	...	'736
16'3mm. Al	'407	...	...	'877	...	...
" "	'416	...	1'086	...	...	...
" "	'422	...	...	...	'804	...
" "	'462	...	...	...	'804	...
" "	'480	...	...	...	...	'736
9'8mm. Al	'580	1'126	'925	...	...	...
" "	'616	...	...	...	'746	...
" "	'635	...	...	'803	...	...
" "	'69	...	...	...	...	'610
6'5mm. Al	'75	'946	...	...	...	...
" "	'79	...	'812	...	'672	...
" "	'88	...	...	'708	...	...
" "	'955	...	...	...	...	'497
3'25mm. Al	1'09	...	...	...	'548	...
" "	1'12	'784	...	...	...	...
" "	1'26	...	'683	...	...	...
" "	1'48	...	...	'543	...	...
" "	1'50	...	...	...	...	'339
1'40mm. Al	1'83	...	...	...	'358	...
" "	2'125	...	...	...	...	'252
None	2'42	...	...	...	'321	...
" "	3'25	...	...	...	...	'172
" "	3'60	...	...	'334	...	...
" "	3'70	'492	...	...	...	...
" "	3'97	...	'423	...	...	...


Intensity of Corpuscular Radiation (by Ionisation of Hydrogen)
Intensity of Primary Radiation (by Air-Electroscope)
← Vertical Scale - Arbitrary →
1·5
1·0
0·5
0
1·0
2·0
3·0
4·0
μ/ρ Al.
Seccotine
Paper
Aluminium
Copper
Lead
GRAPH III.

E.S.A. LONDON


Intensity of Corpuscular Radiation (by Ionisation of Hydrogen)
Intensity of Primary Radiation (by Air Electroscope)
Arbitrary Scale
1·5
1·0
0·5
0
Seccotine
Paper
Aluminium
Copper
Lead
GRAPH IV.
5·0
10
15
20
Frequency X10⁻¹⁸
5
2
1
0·75
0·5
0·4
0·3
0·25
0·2
0·175
0·15
0·14
0·3
λ (A°)

The absolute value of the ratio for seccotine was from 15 to 20 per cent less than that for paper, from which it was concluded that this substance was composed of elements which on the average were lighter than the elements contained in paper.

The scale of ordinates has been chosen so as to have the curves in the order of their average atomic weight, with the lightest substance at the top. We notice that with decreasing wave-length (increasing frequency) the ratio

$$\frac{\text{Ionisation of } H_2 \text{ by plate}}{\text{Ionisation of Air}}$$

increases steadily to begin with. This is to be explained by the fact that whereas the ionisation of air is produced by the corpuscular radiation from a fixed mass of air, that of hydrogen is produced by corpuscles from a mass of the material of the plate which increases with shortening wave-length, the faster corpuscles being able to escape from a greater depth. This ceases to be effective when the velocities are such that these which leave the surface of the plate travel right across the chamber without losing an appreciable fraction of their energy. Hence we find all the curves ultimately cease or show a tendency to cease rising (see Graph IV). Confining our attention to Graph IV, all the curves possess a comparatively straight part on the left. These, when produced downwards cut the frequency axis

very near to the origin in the case of seccotine and paper, but the intersections in the other cases are distinctly to the right of the origin. (The points where these curves intersect the frequency axis are of course independent of the ordinate scale. The latter has been adjusted to make the straight parts of the curves nearly parallel so as to bring out the similarity between the curves. The scale for seccotine could not be so adjusted without interfering with the paper curve). As in the comparison of the SO_2 and Ethyl Bromide curves, we find a strong resemblance between the curves when the Al, Cu and Pb curves are displaced bodily to the left a distance of 1·5, 2·7 and 3·6 cm. respectively, and the explanation advanced is the same, namely, that the corpuscular energy is proportional to $\nu - \nu_1$, and the ratio which is plotted as ordinate depends primarily on the emitted energy. (ν is the frequency of the absorbed X-ray, and ν_1 is the frequency of the energy level from which the corpuscles are ejected.). The values of ν_1 obtained from this graph are 1·5, 2·7 and $3·6 \times 10^{18}$ for Al, Cu and Pb, respectively. The values of ν_K for Al and Cu and of ν_L for Pb, obtained from Moseley's papers are 0·36, 1·95 and $3·04 \times 10^{18}$, respectively. Taking into account the fact that we have a certain proportion of faster corpuscles from the lower levels in each case, we should have expected ν_1 to be slightly less than ν_K for Al & Cu and ν_L for Pb,

respectively, whereas the opposite is the case. The method of finding values for $\nu_{1\lambda}$ from the curves, is, of course, crude and can only be expected to give values which are of the right order of magnitude, which they do.

When the curves in Graph IV are compared in the region to the right of λ = 0·4 A°, we find that the seccotine curve begins to rise relative to the other curves when the wave-length is reduced below 0·37 A°. A similar effect is observed in the case of paper at wave-length 0·32A°. In the case of aluminium the effect takes place at 0·215 A°. The last is not so easily seen by an examination of the Graph, but a direct comparison between the ionisations of H_2 by paper and Al, and by Cu and Al by using two identical ionisation-chambers placed in symmetrical positions with respect to the Coolidge tube (see Fig.I.) showed that the ionisation by Al begins to increase abnormally when the radiation is hardened beyond μ/ρ Al = 0·4. This corresponds to the wave-length given above, 0·215 A°. The magnitude of the increase relative to copper was about 10 per cent, by the time the radiation had reached the value μ/ρ = 0·35, that is, when the wave-length had diminished to 0·165 A°. Converting values of μ/ρ to wave-length by referring to the values found by Siegbahn, and by Hull and Rice for the μ/ρ for Cu for characteristic radiations, and using Graph I in the present paper to connect between μ/ρ for Al and μ/ρ for Cu, we get a more accurate set of values for these discontinuity

wave-lengths:-

*Seccotine .	0·47 A°.
Paper . .	0·405
Aluminium .	0·275 .

(It will be noticed that the values obtained by using the general formula, mentioned earlier, are considerably in error. The J-discontinuities of Barkla and White occurred at 0·42, 0·39 and 0·37 A° for carbon, oxygen and aluminium, respectively. The results cannot be said to correspond very well and it is doubtful if they arise from the same cause, for the conditions in the experiments on ionisation of H_2 were as nearly identical with those on absorptions described above as could be wished, and in the latter there was decidedly no trace of J-discontinuities. It might be expected that, by the conservation of energy, an abnormal increase in corpuscular emission should be accompanied by an abnormal increase in absorption, but there is not the slightest trace of an irregularity in the absorption by paper as compared with that by copper in the region of 9·0 μ/ρ Cu (where it would be looked for). The

* The constitution of this substance was presumed to be lighter than that of paper on account of the fact that the ionisation in the former case was about 15 to 20% less than in the latter, for the same incident radiation. This would account for the appearance of the irregularity at a longer wave-length in the case of seccotine. There are clearly insufficient observations to separate the discontinuities for the several light elements which are contained in the two substances seccotine and paper, respectively.

natural conclusion is that the absorption is normal and the enhanced corpuscular emission when the wave-length of the X-ray is reduced below 0·405 Å is due to some transformation which takes place subsequent to absorption. It must be borne in mind, however, that a sudden increase in the ionisation of hydrogen by corpuscles from paper does not necessarily mean an equivalent increase in the energy of corpuscular radiation emitted per unit mass of paper, unless the excess corpuscles are emitted with the same speed as the others. If the excess ionisation is produced by slow electrons, only a comparatively thin layer of paper can contribute to it, so that the extra energy emitted per unit mass must be greatly in excess of the additional ionisation. Conversely, if a small amount of additional energy is absorbed in association with the emission of slowly moving electrons, the additional ionisation of H_2 may be too small to be noticed. The suggestion I wish to put forward is that with decreasing wave-length, the energy which goes to provide this additional corpuscular radiation has been increasing gradually, not abruptly, that the corpuscular velocity has also been increasing gradually. An increase in velocity alone (at the expense of number emitted per unit mass, i.e. assuming the total energy constant) would enhance the ionisation of hydrogen, a greater thickness of paper taking part,

so that a simultaneous increase of energy of corpuscular radiation and speed of emission of the corpuscles will produce a combined and therefore a more sudden effect than the gradual increase of absorbed energy would lead us to expect. A.H.Compton's quantum-theory of scattering seems to give a possible explanation of the irregularities under consideration. He has predicted that a corpuscular radiation will be found to be associated with the phenomenon of scattering when the X-radiation is hard, and that the absorption associated with this corpuscular radiation will be found to be

$$\sigma_a = \frac{\alpha}{(1+2\alpha)^2} \cdot \sigma_0$$

where α = 0·0242 / λ (Å), λ is wave-length in Ångstrom Units.

and σ_0 = the classical value of the scattering coefficient

= 0·2 × the density of the absorbing substance.

The true-absorption-coefficients of hard X-rays for paper and aluminium are almost entirely associated with corpuscular emission. The total absorptions associated with corpuscular emission are therefore approximately proportional to

$\bar{\mu}$ (Paper) + σ_a and $\bar{\mu}$ (Al) + σ_a for paper and Al, resply.

The additional absorption associated with scattering (corp^r) at the points where the discontinuities appear (0·405 and 0·275 Å) amount to 8·0 per cent and 6·4 per cent respectively, and this percentage has just begun to increase fairly rapidly with diminishing wave-length in both cases.

(Note:- The 6·4% is for corpuscles of higher velocity (the wave-length 0·275 Å being shorter) than the 8% and on this account is possibly as effective in ionising the hydrogen as the 8% from paper).

Compton's theory therefore seems to indicate that the corpuscular emission associated with scattering is becoming important in the case of paper and aluminium at the wave-lengths where the present experiments show an increase in the corpuscular emission from these substances. Further agreement with this theory appears when we consider the absorption curves in Graph I. The straight lines drawn through the observations in the case of paper and Al intersect at about 0·2 μ/ρ for Cu. Here the values of the mass-absorption-coefficients, instead of being 0·2, as the classical theory of scattering would predict, are found to be about 0·16. Compton's theory corrects the classical coefficient by multiplying it by the factor $1/(1 + 2\alpha)$, where α is, as before, $0{\cdot}0242/\lambda(\text{Å})$. Assuming for the moment that the correction is correct, if we add to the observed values of the mass-absorption-coefficient the quantity,

$$0{\cdot}2\left(1 - \frac{1}{1 + 2\alpha}\right),$$

we should obtain the values of the mass-absorption-coefficient which would have been obtained had the classical theory been correct. When this is actually done, the new values fall as well on a straight line as before, but the straight line is raised on the left by 0·0275, (μ/ρ at Cu=3'8) and on the right by 0·015 (μ/ρ Cu=24.). When this straight line is produced to the left, the "zero" value of the mass-absorption-coefficient is found to be 0·195, which

is remarkably near the classical value , 0·20.

The correction to be applied to the scattering coefficient is the same for all substances, so that clearly the same procedure as we have just carried out with the paper curve will raise the Al curve an equal amount, that is, to very nearly the classical value.

Scattering Experiment.

We have been led to the conclusion in discussing the previous experiment, that certain irregularities which appeared, might reasonably be explained on Compton's theory of scattering. From this point of view the excess ionisation of hydrogen by seccotine, paper and aluminium when the wave-length is short is to be attributed to the process of scattering, the electrons which scatter the radiation retaining the difference in vector momentum between the primary and the scattered quanta. If this theory is correct the energy of the excess corpuscular emission must be taken from that part of the primary absorption which gives the scattered radiation, only a fraction of the scattered absorption reappearing as X-radiation. If it could be shown by experiment that the energy scattered in the form of X-radiation was less than the energy absorbed in association with scattering, we should have qualitative proof that we had correctly traced the origin of the excess

corpuscular radiation. The agreement already pointed out between Compton's theory and experiment with regard to the total energy absorbed in the process of scattering in the case of paper and aluminium leads us to suppose that Compton's calculated value for the absorbed energy is at least very close to the truth. If then we can measure the quality and intensity of the scattered radiation in a number of directions for different wave-lengths, and compare these with the values calculated on Compton's theory, agreement between experiment and theory would prove that only a part of the energy absorbed in the process of scattering re-appears as X-radiation.

In the experiment about to be described the intensity and quality of the radiation scattered by paper at right-angles to the primary beam were measured, the intensity being measured in arbitrary units. (Compton's theory gives very approximately the same results as the classical theory when the wave-length is long, so that the absolute determination of the intensity seemed unnecessary).

The apparatus used for the experiment was set up as in Fig.II. The cathode stream was arranged to be directed at right-angles to the primary X-ray and at an angle of 45° to the horizontal, that is to the direction of the pencil of the scattered X-ray which was to be tested. This ensured that polarised and unpolarised rays would be scattered in the same proportion in a horizontal direction. The scattering

substance was set accurately at 45° to the primary beam in a vertical plane, the normal to the emergent side of the radiator facing so as to bisect the right-angle subtended at the centre of the radiator by the primary and secondary ionisation-chambers. A quantum of radiation scattered into the secondary ionisation-chamber will by this arrangement traverse on the average (and if the apertures are not very large, in each individual case) the same thickness of the radiator as the unscattered which passes on to the primary ionisation-chamber. If the radiator is thin, that is to say, if it absorbs only a small fraction of the radiation, and if the quality of the secondary is nearly the same as that of the primary radiation, the absorption effect of the radiator will be the same on both primary and secondary.

The intensity of the two beams was measured by two ionisation-chambers of the same dimensions, those in fact which were used in the experiments described above. They were cylindrical in form, the radiation entering in the direction of the axis. The length was 14cm. and the diameter 10cm. They were connected to electroscopes underneath of the box-form already described. The same gas was used in both - SO_2. The windows were of aluminium 0·1 mm. thick and the other ends of Al 1·5 mm. thick. The enormous difference in intensity between primary and secondary made it necessary to make a corresponding difference in the sizes of the apertures which restricted the beams entering the two chambers. The primary pencil

was about 0·5 mm. and the secondary about 3 cm. in diameter. To ensure "saturation" in the case of the primary where the ionisation was by a fine intense pencil of radiation, that is, to ensure that the amount of recombination before the ions were separated and discharged was negligible, a straight piece of Al wire was used as electrode and set parallel to the pencil of radiation and about half-an-inch below it. The ions were thus subjected to a strong tranverse field. The electrode in the case of the secondary was a circle of Al wire covered with a fine cotton mesh and placed transversely to the axis. The broad beam entering this chamber was not wide enough to strike the electrode.

Diaphragms of lead were placed in such a way as to reduce stray effects* (chiefly lead L-radiation) to a minimum. Two were placed in the primary between the tube and the radiator, two between the radiator and the primary chamber and two between the radiator and the secondary chamber. In addition, diaphragms were placed immediately in front of the chambers. Filtering sheets were placed at A (Fig. II.) and absorbing sheets at A, B and C. The amount of radiation scattered by the absorbing sheets into the chambers was negligible. Fig, II is drawn to scale (1/10). All lead close to the radiator was covered with Al to prevent tertiary lead L-radiation from

* A test for stray effects showed that they were very small and of the order that would be produced by the scattering from the air in the region of the radiator.

reaching the secondary chamber.

Let R_1 be the ratio of secondary to primary ionisation when only the filter intercepts the radiation. The ratio when a thickness x of Al is placed at A is given by

$$R_1 \times \frac{e^{-\mu x}}{e^{-\mu x}} = R_1 \text{ (unchanged),}$$

where μ is the absorption coefficient of the primary, supposed homogeneous. The ratio when x cm. of Al is placed at B and at C is given by

$$R_1 \times \frac{e^{-(\mu + \delta\mu)x}}{e^{-\mu x}} = R_2 \text{ , where } \mu + \delta\mu \text{ is the}$$

absorption coefficient of the secondary. Hence

$$\log_e (R_1/R_2) = x\,\delta\mu \text{ , which gives } \delta\mu.$$

The ratio when x cm. of Al is placed at B only is given by

$$R_1 \times \frac{1}{e^{-\mu x}} = R_3 \text{ , so that}$$

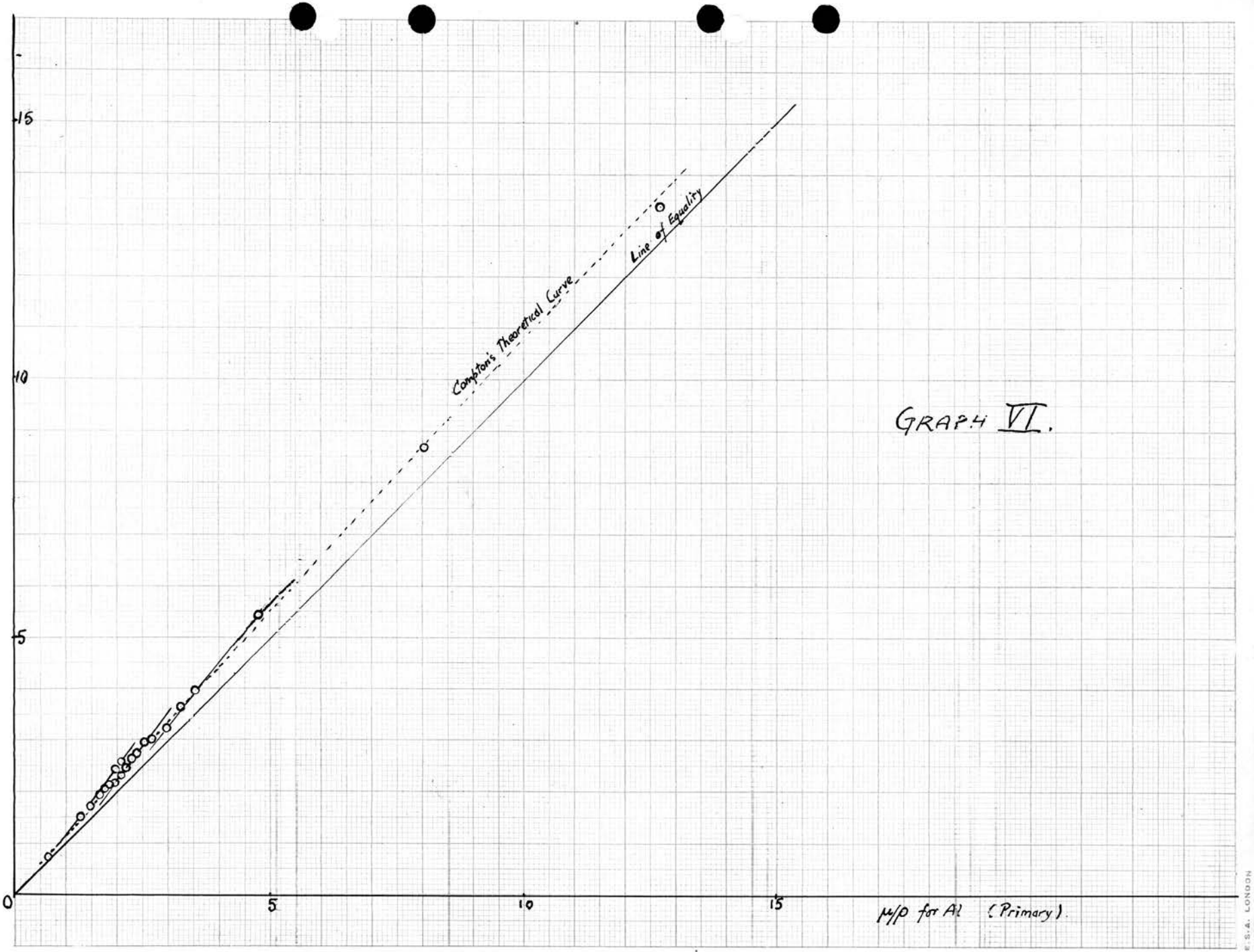
$$\log_e (R_3/R_1) = \mu x \text{ , which gives } \mu.$$

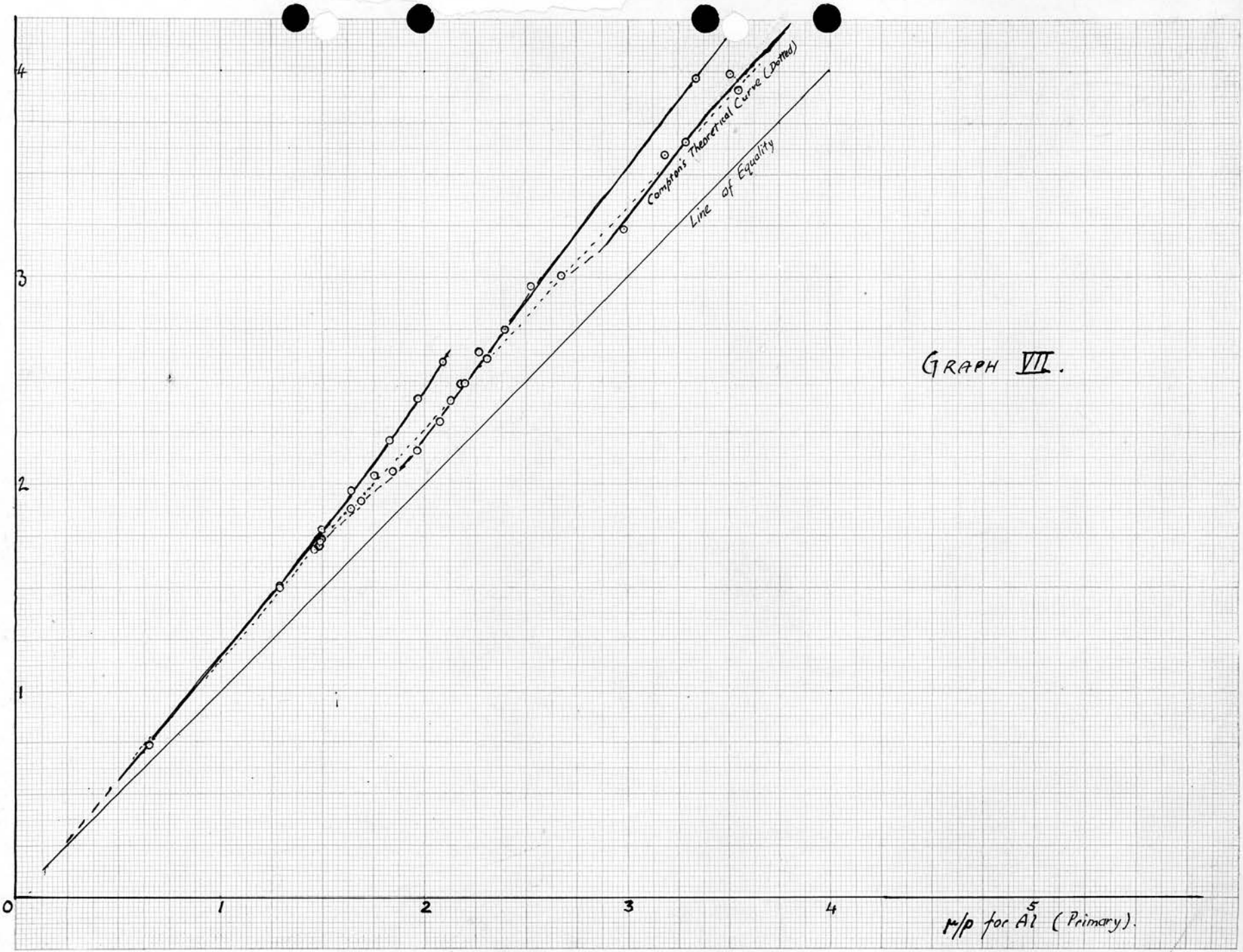
A few observations were taken in this way with 268 sheets of filter-paper as radiator, a considerable number were taken with 50 sheets and one observation with 15 sheets. The results are given in Table VIII, and are shown graphically (Graphs VI and VII). The mass-absorption- coefficients of the primary are plotted against those of the secondary. Compton's theory requires

TABLE VIII.

Scattering by Filter Paper.

Radiator	Filter Al	μ/ρ Al Primary	$\delta(\mu/\rho)$ Observed	$\delta(\mu/\rho)$ Qu. Theory
268 sheets	Nil.	2·09	0·50	0·27 ×
	••	1·49	0·29	0·21
	••	1·49	0·23	0·21
	••	2·27	0·37	0·28
	3·66 mm.	0·65	0·092	0·106
50 sheets	Nil	3·55	0·36	0·38
	••	3·29	0·37	0·35
	••	4·78	0·65	0·47
	0·4 mm.	3·34	0·63	0·37 ×
	••	3·19	0·41	0·35
	0·3 mm.	3·51	0·48	0·38
	0·6 mm.	1·97	0·445	0·26 ×
	••	2·31	0·30	0·29
	••	2·40	0·35	0·29
	••	2·20	0·29	0·28
	••	2·13	0·275	0·27
	••	2·18	0·31	0·28
	••	2·08	0·23	0·27
	••	1·96	0·19	0·26
	0·92 mm.	1·64	0·325	0·23 ×
	••	1·69	0·23	0·24
	••	1·85	0·21	0·26
	1·36 mm.	1·30	0·205	0·19
	••	1·48	0·22	0·21
	0·5 mm.	2·68	0·33	0·31
	••	2·53	0·425	0·30 +
	••	2·98	0·245	0·34
	1·36 mm.	1·29	0·23	0·19
	••	1·46	0·235	0·21
	1·31 mm.	1·76	0·285	0·24
	••	1·64	0·245	0·23
	••	1·83	0·38	0·26 +
	Nil	8·03	0·67	0·70
15 sheets	••	12·7	0·69	0·90


μ/ρ for Al. (Secondary from Paper).
15
10
5
0
5
10
15
μ/ρ for Al (Primary)
Compton's Theoretical Curve
Line of Equality
GRAPH VI.



GRAPH VII.

an increase in wave-length in scattering of 0·0242 A° for all wave-lengths scattered at 90°. From a knowledge of relative values of wave-lengths and mass-absorption-coefficients for Al (approximate values are good enough for the purpose) the theoretical values of μ/ρ may be calculated for the secondary radiation, i.e. $\mu/\rho + \delta(\mu/\rho)$. This was done and the theoretical values of $\delta(\mu/\rho)$ are tabulated along with the experimental values. Also the theoretical curve for μ/ρ (primary) against μ/ρ (secondary) is shown dotted in Graphs VI and VII. The observations are seen to agree fairly well with the theoretical values on Compton's theory. The agreement is sufficiently close to conclude that Compton's theory gives the change in penetrating power to the correct order of magnitude. If we can now show that the relative intensities of primary and secondary are of the order predicted by Compton, our results will be consistent with the view that only part of the energy absorbed in the process of scattering appears as scattered X-radiation. (To prove this view correct would involve an examination of the radiation at a number of angles from the direction of the primary radiation. Nevertheless agreement between theory and experiment at one angle would give strong support to the theory).

Let λ = the wave-length of the primary,

$\lambda + \delta\lambda$ = ... secondary,

then $\delta\lambda = 0{\cdot}0242$ A°, and if $\alpha = 0{\cdot}0242/\lambda$ (A°), the relative intensities (secondary / primary) are proportional to $(1 + \alpha)/(1 + 2\alpha)^2$. (Compton.)

Let μ and $\mu + \delta\mu$ be the absorption-coefficients of the primary radiation and secondary radiation respectively for the gas in the ionisation-chambers, then to a fairly close approximation the relative absorptions by a column of the gas of finite length l (the length of the ionisation-chamber) will for a given intensity be $((\mu + \delta\mu)/\mu)$, for secondary / primary, and this fraction gives also the relative ionisations.

The observed values of

$$\frac{\text{Ionisation of Secondary}}{\text{Ionisation of Primary}}$$

for a range of wave-lengths should therefore be proportional to

$$\frac{1 + \alpha}{(1 + 2\alpha)^2} \times \frac{\mu + \delta\mu}{\mu} .$$

Now μ varies as λ^3 so that $\delta\mu/\mu = 3\,\delta\lambda/\lambda = 3\alpha$. It follows at once that to the first order of α (which is ·08 at most in the present range of wave-lengths, so that α^2 is about half a per cent at most) the ratio of the ionisations should be proportional to unity, that is the ratio should be constant. Within the limit of experimental error, that is, to about two-per cent the ratio was found to be constant. We may thus conclude

that not only is the change of wave-length given by Compton of the right order but the diminution in intensity of the scattered radiation with shortening wave-length is confirmed quantitatively to a fairly close approximation.

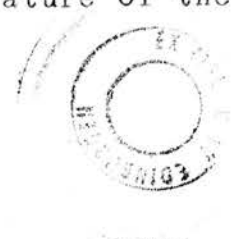
In plotting the experimental values of μ/ρ for Secondary against μ/ρ for Primary (Graphs VI and VII) there is an indication that the experimental curve is discontinuous, that it consists of at least two, and possibly three smooth curves, which lie in echelon, thus giving where the curves overlap, two values of the ordinate for one of the abscissa. It will be noticed in Graph VII that the circles (which represent single observations and not averages of observations) lie very close to one or other of the smooth curves drawn, so close, in fact, that in practically every case there is no doubt as to which curve the circle belongs. As every observation taken has been represented by a circle in the Graph, this would seem to indicate that the discontinuities are real and not due to experimental error. The higher values of μ/ρ Secondary (where there are two for the same value of μ/ρ Primary) are much less numerous than the lower, so we may consider the higher value the exceptional case. The lower values are of the order calculated on Compton's theory. It should be pointed out that the higher values were not obtained consecutively. Table VIII gives the observations in the order in which they were taken, and those which definitely gave the

higher values, that is the exceptional values, (six in number), are marked with a cross. It will be noticed that the higher values are distributed fairly uniformly throughout the series. Their appearance cannot therefore be attributed to any temporary fault in the apparatus. The probability that these higher values are genuine is strengthened by the fact that other observers in this laboratory have found discontinuities of a similar kind and at practically the same wave-lengths in performing the experiment under different conditions.

A comparison was made between the conditions of experiment which gave what we may call a normal value and those which gave an exceptional value for μ/ρ Secondary. The only difference found was that when an exceptionally high value was obtained for μ/ρ Secondary, the μ/ρ Primary was distinctly smaller than would have been expected from the resistance in the primary circuit of the induction-coil. This would indicate that it was the Primary μ/ρ which was exceptionally small, and the Secondary μ/ρ was possibly normal. This has suggested a possible explanation. The scattering of X-radiation is known to be more and more concentrated in the forward direction as the wave-length is diminished. This has been shown by experiments on γ-rays, and is also required by Compton's theory. If we suppose the K-lines of tungsten from the anticathode are sufficiently short in wave-length to be influenced to a very appreciable extent by this abnormal

distribution at the hard end of the spectrum, then we may get two very different values of μ/ρ Secondary for the same value of μ/ρ Primary by assuming that in one case the K-lines of tungsten were not excited, and in the other they were, the radiation in the latter case being presumably more heterogeneous. In the Secondary the K-radiation would not be scattered at 90° to the same extent as the softer components of the general radiation. Consequently, on the average, the Secondary beam at 90° would be too soft. The radiation used in this experiment was very heterogeneous, the small intensity of the Secondary making it impracticable to filter the radiation to any great extent. With a knowledge that the fraction of the primary radiation scattered at 90° depends on the wave-length, it would seem that the measure of the penetrating power of the secondary as compared with that of the primary with heterogeneous beams would not only give no more than an average value, but would give different values for μ/ρ Secondary for a given μ/ρ Primary corresponding to different distributions of energy in the spectrum of the heterogeneous beam. The appearance of irregularities in the results which are greater than the experimental error would lead us to expect, might therefore be justly attributed to variations in the heterogeneity.

It would seem futile to attach much importance to such irregularities, when the exact nature of the heterogeneity is not known.



Summary.

Experiments on the relative absorptions of X-rays by copper, aluminium and paper under conditions detailed show that under these conditions the J-discontinuities of Barkla and White do not appear. The results indicate that the absorption associated with scattering falls below the classical value by an amount which agrees very well with that calculated on the quantum-theory of scattering of A. H. Compton.

Experiments on the ionisation of SO_2 and Ethyl Bromide indicate that the velocity of emission of corpuscles is very probably that which corresponds to energy $h(\nu - \nu_1)$, where ν_1 is the frequency corresponding to the energy level of the expelled electron. They also give a slight indication that the corpuscular emission from air increases relative to these gases with shortening wave-length when the latter is reduced below about 0·4 A°, but the evidence is marred by the presence of "end-losses" which cannot be accurately allowed for. The J-discontinuities in corpuscular emission did not appear.

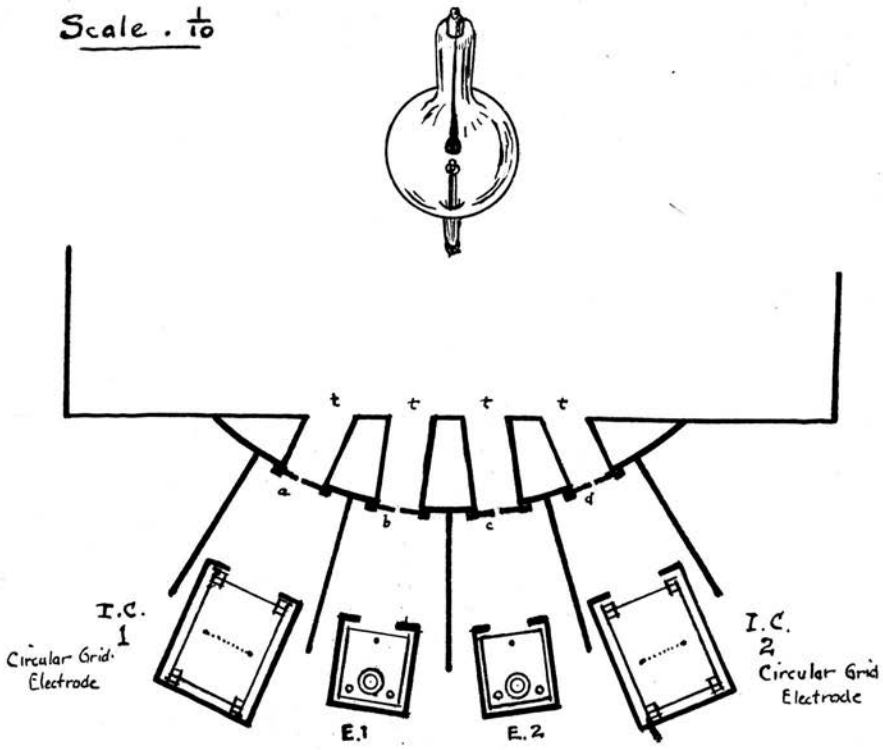
Experiments on the corpuscular emission from plates of seccotine, paper, aluminium, copper and lead, as measured by ionisation of hydrogen, indicated, as in the experiments on SO_2 and Ethyl Bromide, that the corpuscles in the case of Al, Cu and Pb left the atom with less than the full quantum of energy. They showed that the lighter elements emitted an additional corpuscular radiation when the wave-length of the incident radiation was short, that the energy required for this

excess emission produced no apparent discontinuity in the absorption curve for paper, but they lent support to the view of Compton that a corpuscular emission would be found in association with scattering when the primary was of short wave-length.

An experiment on the scattering of X-rays by filter-paper showed that the change in quality and the variation in intensity of the scattered radiation required by Compton's theory were confirmed over a considerable range of wave-lengths for scattering at right-angles to the primary. From this it was deduced that the scattered X-ray was probably carrying only a fraction of the energy absorbed in association with scattering, thus strengthening the probability that the excess corpuscular emission observed in the previous experiment was to be attributed to the scattering process.

In conclusion, I wish to take this opportunity of thanking Professor Barkla for much valuable help and advice, and for the keen interest he has taken in these experiments, which were carried out under his direction and supervision.

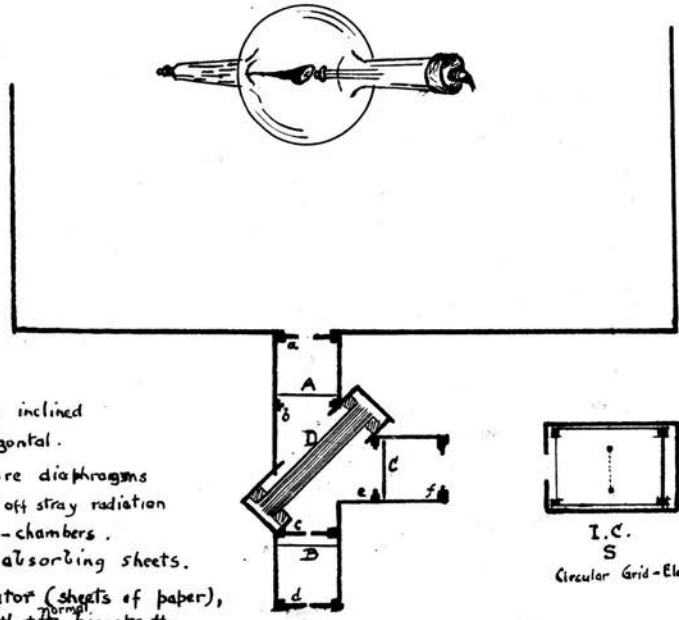
Scale . $\frac{1}{10}$



The Coolidge Tube is placed so that the Ionisation-Chambers (I.C. 1 & 2) lie symmetrically with respect to it. The latter are connected to Wilson Electroscopes underneath. Rays from the tube pass directly into two other Electroscopes (E.1 & E.2). t,t,t,t are tubes of lead which serve to cut down to a negligible amount, stray radiation (particularly Lead Rays) from the box containing the tube. a,b,c,d are diaphragms of Lead. These are generally shaped so as to prevent incidence of the radiation on the electrodes.

Filters and Absorbers are placed at a,b,c,d.

FIG. I.



Coolidge Tube is inclined at 45° to the Horizontal.

a, b, c, d, e, f are diaphragms of lead. They cut off stray radiation from the ionisation-chambers.

A, B, C are absorbing sheets.

D is the radiator (sheets of paper), and is placed so that the Normal bisects the angle between Secondary and Primary Beams. (A, D, B, C)

The whole apparatus is encased in lead during observations.

The Ionisation Chambers (I.C. P and I.C. S) are connected to Wilson Electroscopes.

I.C.
S
Circular Grid-Electrode

I.C.
P
Rod-Electrode parallel to axis and 1" below it.

FIG. II.